PREDICTION OF VEHICLE MOBILITY ON LARGE-SCALE SOFT-SOIL TERRAIN MAPS USING PHYSICS-BASED SIMULATION

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The off-road vehicle mobility response on various types of soils and for various vehicle configurations is of great importance to the Army as well as other departments of the military. Mobility measures include: speed-made-good, go/no-go map, energy/fuel consumption, and the vibrations transmitted to the occupants/payloads. Currently the Army uses the NATO Reference Mobility Model (NRMM) [1, 2] to predict the mobility measure, namely, the speed-made-good. NRMM was developed from the 1970's to 1990's and is based on empirical relations which are hard to generalize especially for new vehicle designs since they were not used to calibrate the empirical relations used in NRMM.

The objective of this paper is to present a high-fidelity physics-based approach to accurately and reliably predict the vehicle response measures, which will allow for independent testing and validation of the model components such as soil type, tire/track, powertrain system, vehicle suspension system, and traction control system rather than having to experimentally measure the response for each vehicle configuration and soil type. The modeling approach is based on (i) a seamless integration of multibody dynamics and discrete element method (DEM) solvers, and (ii) using a Design-of-Experiments (DOE) to predict the off-road soft soil mobility of ground vehicles on large-scale terrain maps.

The vehicle is modeled as a high-fidelity multibody dynamics model which includes models of the various vehicle systems including chassis, wheels/tires, suspension system, steering system, and power train. A penalty technique is used to impose joint and contact constraints. An asperity-friction is used to model joint and contact friction. A proportional derivative (PD) controller is used to control the speed of the vehicle while a steering controller is used to ensure that the vehicle follows a desired path. The soil is modeled as a Discrete Element Model (DEM) with a general cohesive material model that is suitable for mud and snow type materials. Then the governing equations of motion of both the vehicle and the soil particles are solved along with joint and contact constraints using a time-stepping explicit integration procedure.

The DEM soil model can account for the soil cohesion, compressibility, plasticity, fracture, friction, and viscosity. Particles with only translational coordinates are used as DEM particles. The particles have a maximum unconsolidated radius and when the particles are compressed that radius is reduced by the amount of plastic deformation. The primary soil material parameters considered in this study are the soil cohesive strength and the internal friction angle. Following the NRMM practice, we will measure the soil strength using the cone index. The particle cohesive/adhesive strength and the particle friction coefficients are calibrated

using a simulation of a cone penetrometer experiment to yield a desired cone index (Figure 1) according to the Mohr-Coulomb Theory.

In the simulation to predict the vehicle's speed-made-good and other mobility measures (Figure 2) the terrain is set at a certain desired grade. The simulation starts by leveling and consolidating the soil. This is achieved by compressing the soil to a desired consolidation stress using a lid, after which the lid is removed. This step is essential for cohesive soils since consolidated soil is much stronger than loose unconsolidated soil. Next the vehicle is commanded to slowly accelerate from rest to its maximum speed. The actual steady-state maximum vehicle speed in the desired travel direction is the speed-made-good and the rest of the vehicle mobility measures are also extracted at this steady-state.

If the vehicle follows the desired velocity profile then to reach its maximum speed the vehicle needs at least a 312.5 m long terrain patch. With a patch width of 3.5 meters, soil depth of 0.6 meters, and consolidated particle size of about 26.5 mm, the required number of particles about 67,000 particles per meter of terrain. So for, say, a 400 m long terrain patch about 27 million particles will be needed. At current simulation computational speeds a 35 sec simulation with 27 million particles will take about 7 months to complete. In order to perform the simulation in a reasonable amount of time (5 days) a moving soil patch strategy is used in this paper. This is achieved by only simulating the DEM particles which are close to the vehicle. The DEM particles which are far behind the vehicle are continuously eliminated and then reemitted as new particles and leveled/compacted in front of the vehicle. This ensures that the number of DEM particles remains relatively small even for arbitrarily long vehicle travel distances. In the present paper a 9.3 meters moving terrain patch is used.

The following design-of-experiments strategy will be used to predict the "speed-made-good" and other mobility measure distributions over large terrain maps. The rectangular terrain map, say 20 km × 20 km, is divided into 20 m × 20 m grid cells. For each grid cell the maximum slope and the minimum soil cone index are extracted. Then, the maximum positive slope and the minimum and maximum cone indices for the entire terrain map are found. The positive grade range of the terrain map (say from 0 to 30^o) is quantized into a certain number of values (say 11). Also, the cone index range (say from 30 to 300 psi) is quantized into a certain number of values (say 18). Then a vehicle mobility simulation is performed for each of the 11×18 combination of slope and cone index. For each combination the various steady-state vehicle mobility measures are calculated. Then the mobility measure values are bi-linearly interpolated from the calculated values to the actual values for each terrain grid cell. A map of the mobility measure over the entire terrain map is then generated. For example Figure 3 shows a typical speed-made-good distribution over a 22×22 km terrain map for a Humvee-type vehicle.

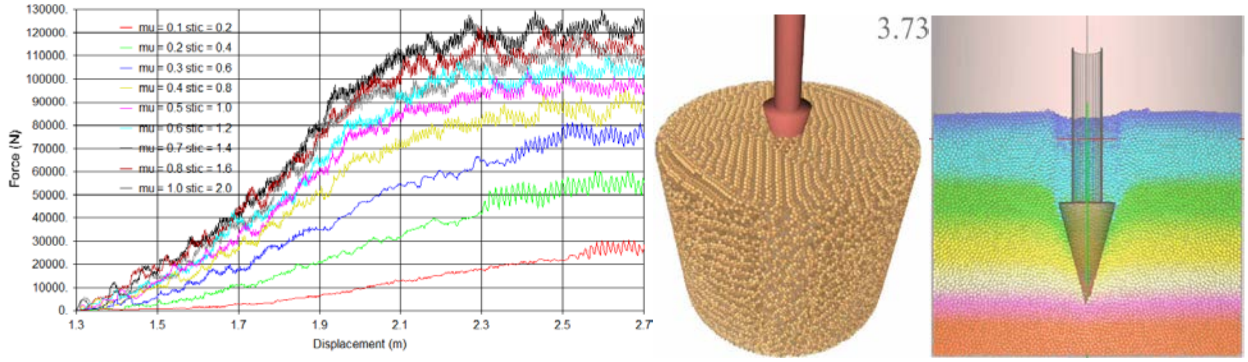

Figure 1. Cone penetrometer simulation for different particle friction coefficients and adhesion/stiction factors.

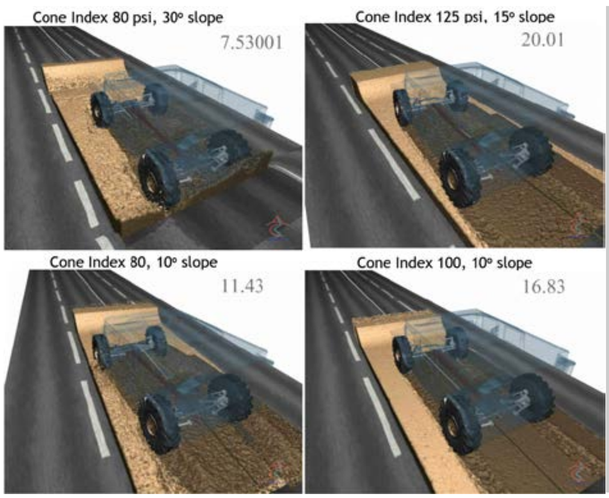

Figure 2. Snapshots of a Humvee-type vehicle going over terrains of various slopes and cone indices.

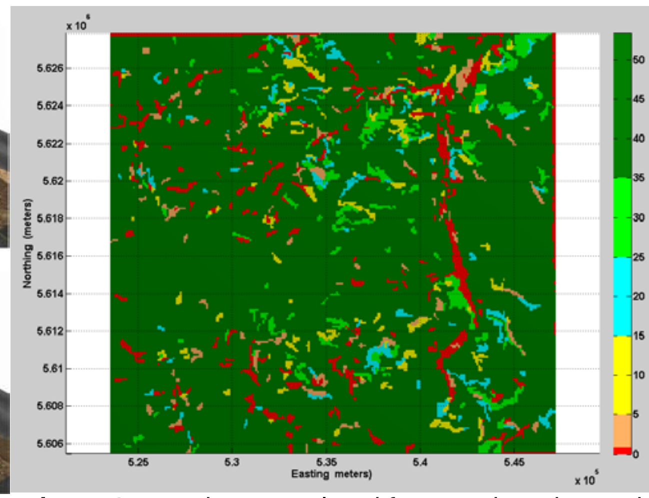

Figure 3. Terrain map colored for speed-made-good (22 km x 22 km).

References

1. Haley, P., Jurkat, M., and Brady, P.J., "NATO Reference Mobility Model, Edition I, Users Guide," Technical Report Number 12503, U.S. Army Tank-automotive and Armaments Command, Warren, MI, October, 1979.
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